Part Two

An Integrated Strategy for Solar System Exploration

The material in Part One, together with community input received in various forms, provides the basis for the strategy for solar system exploration outlined in Part Two of this report. This broad strategy addresses all aspects of the Solar System Exploration program: its motivations, its infrastructure, future and present missions, its relationship to other programs in NASA and elsewhere in government, and supporting ground-based facilities.

Chapter 6 addresses the motivations for the program, briefly describes the strengths and weaknesses of important elements of the program's infrastructure, and makes recommendations for addressing the latter. It makes clear why solar system exploration is a compelling activity today.

Chapter 7 presents the results of the Solar System Exploration Survey's analysis of the many scientific questions raised in Part One and identifies 12 key scientific questions that the SSE Survey believes are most appropriate to address in the period 2003-2013. Relating these questions to candidate missions suggested to the Survey the scientific basis for the system of flight mission priorities and supporting ground-based priorities presented in Chapter 8.

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Solar System Exploration Today: A Multifaceted Endeavor

Solar system exploration is a grand human enterprise that seeks to discover the nature and origins of the celestial bodies among which we live and to explore whether life exists beyond Earth.

MOTIVATIONS: WHY SOLAR SYSTEM EXPLORATION COMPELS US TODAY

To appreciate our place in the universe, we must understand the neighborhood in which we reside. We want to know how planets formed, what determined their characteristics, and why at least one of them became an abode of life. How haphazard was this formation? Do Earth-like planets typically survive, or are they usually swallowed by Jupiter-like objects, pushed into their parent stars, or flung into the vastness of interstellar space? Is life a rare phenomenon, or is it the expected outcome of solar system formation? The answers to these profound questions may be contained in the orbits, masses, compositions, gaseous and plasma environments, and surface and internal structures of solar system objects. We may understand yet more by scrutinizing the planets orbiting other stars.

The solar system evolves. Planetary and satellite surfaces record ancient histories of violent impacts, volcanic eruptions, crustal tectonics, and fluid erosion. Planetary rings continually change, active geology is at work on the solid bodies in the outer solar system, and Titan's atmosphere supports ongoing organic synthesis. Mars's climate and internal dynamics have changed dramatically over time. Earth-crossing asteroids and comets threaten us. Will we and our planetary home survive? Some day people may live on other planets. By investigating these environments, we can better prepare for our future and perhaps predict the destiny of our species.

Could life have developed on other solar system objects? Recent discoveries suggest that the "habitable zone"[a] is not defined simply by distance from a star. Liquid water appears to be seeping out of the frozen cliffs of Mars and likely lies beneath the icy crust of Europa. Life on Earth survives extreme environments. Organic molecules and chemical-energy sources are ubiquitous beyond our planet, and the ingredients of familiar terrestrial life—water, carbon, and nitrogen—may have been brought to Earth's surface by asteroids and icy comets. Life itself may have been strewn across the solar system's archipelago by the impacts of comets and asteroids.

[a]Throughout this report, the word "habitable" is used in a general sense meaning compatible with any kind of life. When used to mean compatible with human life, the text is qualified as such.

Exploration of the solar system can reveal how likely we are to find life elsewhere in the universe and how it might be recognized. Just as studies of extreme but rarely visited terrestrial environments have revealed novel microbial species and unanticipated microbial ecosystems, so the detailed exploration of the solar system also might revolutionize our ideas about the diversity of life and the range of conditions in which it might originate and/or survive.

The scrutiny of the solar system provides other examples against which to compare Earth. It also helps us comprehend better how our world operates and how it evolves. The study of the solar system as a whole, and of the individual bodies within it, helps us understand how the entire family of planets formed and how planetary systems might develop around other stars. It therefore leads us to wonder whether other Earth-like planets can sustain life.

When we discuss life in the context of solar system exploration, it must be clearly understood that success or failure is not measured according to whether or not we actually find life beyond planet Earth. It is just as important to know that life does not exist in a particular locale, because this may lead to the development of an understanding of the environmental conditions necessary for life's existence. This suggests that life-related studies must be intimately connected to studies of the origin and evolution of planetary environments. Therefore, to assess the habitability of, for example, Mars requires a thorough understanding of that planet's tectonic, magmatic, hydrologic, and climatic evolution, including geochemical cycles of biological relevance, the development of potential habitats, and the processes responsible for the preservation and destruction of biomarkers.

To truly appreciate the apparent uniqueness of Earth, we must understand its rocky siblings: Mercury, Venus, and Mars, as well as the Moon. To uncover clues to the origin and evolution of the solar system and other planetary systems, we must learn about the giant planets and their satellites and ring systems. To understand our beginnings, we must examine samples from the solar system's oldest and most primitive bodies: comets and asteroids.

These issues concerning our place in the cosmos derive from three of the most profound questions that can be posed about the human condition: Are we alone? Where do we come from? What is our destiny? These deceptively simple questions have motivated a broad range of human endeavors, including exploration of scientific subjects as diverse as cosmology and biology. Nowhere are they more applicable than in solar system exploration.

Planetary exploration is also driven in part by our species' seemingly insatiable desire for knowledge and the application of that knowledge to improve the human condition. Such aspirations may be realizable as insight into natural processes and phenomena that affect human society, potential mitigation of hazards to Earth that arrive from space, and provision of knowledge about space resources that are available for utilization. The unquenchable human desire to explore, again ostensibly to improve the human condition, encourages many citizens. And who knows what role is played by the yearning of humans to know ourselves and to comprehend our place in the universe? In the words of T.S. Eliot:

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

—T.S. Eliott, "Little Gidding," *Four Quartets*

A major motivation for much solar system research is to understand, at a fundamental level, the manner in which planetary bodies function. Various scientific disciplines—geology, meteorology, and space plasma physics, for instance—once pertained solely to Earth. Today they are enriched by being addressed in the broader context of the whole solar system rather than with a lone example. This comparative approach can be oversold, but some substantial advances in understanding are indeed being realized by investigating planetary processes as they apply in different settings: high-temperature volcanism on Io, differences in the climates of terrestrial planets, and substorms in Mercury's magnetosphere, for example.

Since time immemorial, a driving impulse for science has been to understand the threats that the natural environment poses to civilization. Some hazards, such as disease, fire, flood, and earthquake, are obvious and have long been the subjects of intensive scientific research. Others, including climate change and the threat posed by cosmic impacts, have received attention by scientists only in the past few decades. The belated recognition of these threats is a consequence of the long time scales between destructive events, not an indication that they are any less lethal than those that have long been known. Indeed, climate change and cosmic impacts are distinguished by their potential to devastate civilization as we know it. It therefore behooves us to systematically assess the magnitude of these threats.

Climate can be altered by modifications in global volcanism, solar output, or the influx of interplanetary dust. Both deterministic and chaotic celestial mechanics introduce variable solar insolation, and society's contaminants affect the atmosphere's response. The interactions among these influences are so complicated that they are not yet fully understood. The atmospheres of Venus and Mars, for example, evolved such that they differ radically from Earth's atmosphere. To learn the reasons for these differences is a central motivation for the SSE Survey's support of a vigorous Mars program and of in situ investigations of Venus. In the latter case, temperatures vastly higher than those on Earth result from a runaway greenhouse effect of a magnitude seemingly incommensurate with Venus's slightly smaller orbital radius. Mars's thin carbon dioxide atmosphere represents the other extreme, in which temperatures are low and a significant fraction of the atmosphere lies buried as ice within the regolith and upper crust. These "end members" of terrestrial atmospheric evolution nicely bracket the thankfully clement climate prevailing on Earth.

The atmospheric, geological, and evolutionary effects of cosmic impact have become apparent only since the early 1980s, when the likely cause of the Cretaceous-Tertiary extinction was first associated with the impact of a 10-km asteroid.[1] Colliding asteroids and comets of even much smaller diameter deliver enormous kinetic energy with possibly deadly consequences ranging from local to global. At Congress's direction, the National Aeronautics and Space Administration (NASA) has supported a ground-based program to identify 90 percent of the near-Earth objects (NEOs) larger than 1 km in diameter by 2008. The task is now about half complete, although the best simulations of the current survey strategies predict that this goal will not be met for many decades.[2]

Kilometer-sized impactors would be globally devastating, and even the much more common smaller projectiles could wreak unimaginable local havoc in populated areas. The high-altitude explosion of an 80-m-diameter body above Tunguska, Siberia, in 1908 felled trees over a 2,000-km^2 blast zone, and would have been sufficient to flatten a large city. Assessment of the NEO population down to 300-m scales, as part of an organized inventory of the small bodies of the solar system, was recognized as a high priority for NASA's Solar System Exploration program in the most recent astronomy and astrophysics decadal survey.[3] We also need refined physical observations of these threatening objects in order to determine their physical properties and estimate their kinetic energy.

Once human exploration of the solar system is renewed, and especially as soon as lengthy missions begin, knowledge of the available extraterrestrial resources will be imperative. Preliminary studies have identified sites where specific resources may be located and have suggested the means to extract these valuable minerals and compounds. Examples include hydrogen "lodes" on the Moon and metallic ore veins through asteroids as well as water and ice reservoirs in the martian regolith.

In summary, solar system exploration has become particularly compelling today because now, nearly half a century after space vehicles first left Earth's gravitational grip, we have finally reached the point where the answers to profound motivational questions seem within our grasp.

SOLAR SYSTEM EXPLORATION: AN INTERNATIONAL ENTERPRISE

The exploration of the solar system is a global endeavor involving scientists, engineers, managers, politicians, and others from many nations, sometimes working together and sometimes in healthy competition, to open new frontiers of knowledge about the solar system. Across the world the program enjoys wide public support, motivated as much by the possible human colonization of the solar system as by specific scientific questions.

Since its inception, solar system exploration has been an international venture. But the early post-Sputnik days of flyby missions and even in situ exploration coincided with the Cold War years, engendering fierce competition between the United States and the Soviet Union. Even during that era the two rivals occasionally cooperated—for example, in the exchange of lunar samples collected by the Apollo and Luna programs as well as in collaborations for the analysis of solar wind interactions with comets. More recently, international collaborative efforts have grown, leading to various programs that have significantly enhanced mission capabilities and scientific returns. International involvement has covered many different aspects of exploration, from individual scientific collaborations and data exchanges to joint major undertakings (e.g., the Galileo, Cassini-Huygens, and Rosetta missions). International collaborations could be strengthened by ensuring strong participation by non-U.S. members on science definition teams for specific projects, as is done for some missions, and by giving further consideration to standing groups such as the International Mars Exploration Working Group.

Some future endeavors are so vast in scope or so difficult (e.g., sample return from Mars) that no single nation is prepared to allocate the resources necessary to accomplish them alone. It would be advantageous to the Solar System Exploration program for NASA to encourage and facilitate such joint ventures so as to allow them to flourish in the future.

The theme of international cooperation appears often in Part Two of this report and **the SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations.**

Nevertheless, primarily because of constraints on its scope, this report focuses only on the status and future of solar system exploration programs in the United States. The SSE Survey attempts to identify where major international cooperation is advisable but in its discussion of future strategy does not consider in any depth the remarkable and exciting plans of other agencies in the international community, nor does it consider the ramifications of international space programs.[4,5]

MODIFYING THE GOALS OF SOLAR SYSTEM EXPLORATION

Solar system exploration has been pursued in the United States for fully four decades. During most of that time, the scientific goals of NASA's Solar System Exploration program have remained quite stable, with their relative importance gradually evolving over time. The SSE Survey largely reaffirms the statement of scientific goals made in the Space Studies Board's last major survey of the planetary sciences,[6] but with the following modifications. First, the SSE Survey includes the search for the existence of life, either past or present, beyond Earth, and second, the Survey seeks to incorporate the development of detailed knowledge of Earth's immediate space environment in order to understand any potential hazards to our home planet.

The objectives of solar system exploration, then, become these:

- Determine if environments capable of sustaining life exist or have ever existed beyond Earth, what parameters constrain its occurrence, how life developed in the solar system, whether life exists or may have existed beyond Earth, and in what ways life modifies planetary environments;
- Understand how physical and chemical processes determine the main characteristics of solar system bodies and their environments, thereby illuminating the workings of Earth;
- Learn how the Sun's retinue of planets and minor bodies originated and evolved;
- Explore the terrestrial space environment to discover what potential hazards to Earth may exist; and
- Discover how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.

In the early years of NASA's Solar System Exploration program, especially during the period surrounding the Apollo explorations of the Moon, space policy was dominated by political goals: for example, President Kennedy's decision to place a human on the Moon by the end of the 1960s. Then and for many years to follow, robotic spacecraft were dispatched on scientific missions designed to simply discover the general nature of the solar system. This era of initial reconnaissance began in the 1960s and encompassed the Mariner missions to Venus, Mercury, and Mars and the Pioneer and Voyager explorations of planets and satellites in the outer solar system, and concluded in the 1990s with the Galileo, NEAR, and Deep Space 1 explorations of asteroids and comets.

Today, as a result, only the myriad newly discovered objects within the Kuiper Belt, including the Pluto-Charon system and related bodies such as Centaurs and Trojans, remain entirely unexplored by spacecraft.

A new phase of exploration began with the Viking missions to Mars (launched in 1975), the Magellan mission to Venus (launched in 1989), the Galileo mission to Jupiter and its satellites (launched in 1989), and the Cassini-Huygens mission now en route to Saturn and Titan. The goals of these missions reflected a new focus: more intensive exploration, including the landing and the emplacement of atmospheric probes. The science objectives advanced from first-order reconnaissance to detailed chemical and physical explorations of selected objects to determine their origins and to ascertain the processes that shaped their identities, and, for the first time, to search for life beyond Earth.

Today, we find the focus sharpening further, following the 1996 announcement that a meteorite, ALH84001, which likely originated on Mars, showed evidence, albeit of a highly controversial nature, of possible past life activity on that planet.[7] The claims concerning ALH84001, though questioned from the outset and now generally discredited, triggered a series of subsequent scientific, political, and programmatic initiatives that have had a very positive impact on solar system exploration. Prime among the benefits was the so called Origins enhancement to NASA's budget for FY 1998. Since then, the Mars component of NASA's Solar System Exploration program has enjoyed increased support and has developed according to strategies sometimes termed "Seek, in situ, and sample" and "Follow the water." These strategies are ultimately aimed at determining the conditions of Mars and whether life ever arose on that planet. The program of geological, geochemical, and geophysical explorations now under way is preparatory to the future return of material samples from Mars to terrestrial laboratories and is directed in part to resolve these questions.

Other observations have initiated this redirection in mission focus. For example, magnetic-field measurements and images from the Galileo orbiter in the late 1990s strongly suggest that a 100-km-deep global ocean of water, a possible abode of life, may currently reside below the icy crust of the jovian satellite Europa. Similar magnetic characteristics also indicate possible subsurface oceans within Ganymede and Callisto. These measurements have prompted NASA to study intensively an orbital mission to begin detailed probing of Europa's putative ocean. Simultaneously, in the crucial area of Earth-based studies, NASA instituted the well-funded Astrobiology program in the late 1990s. Research funded through NASA's preexisting Exobiology program resulted in the discovery of the three-domain, phylogenetic tree of life and revealed the evolutionary significance of organisms from environments previously thought to be incompatible with carbon-based life (e.g., hot springs and deep-sea vents).[8] That such organisms—extremophiles—occur on Earth wherever liquid water exists has expanded our notion of what constitutes a habitable world. This and other related discoveries prompted NASA's increased commitment to the search for life elsewhere in the solar system as a significant aspect of its exploration strategy.

Astrobiology—as does its intellectual precursor, exobiology—has a reciprocal relationship with solar system exploration. It provides guidance for mission design and a framework for interpreting new discoveries. Originally concerned with cataloging observations of phenomena that might be characteristic of life found in regions beyond Earth's atmosphere,[9] astrobiologists now study all processes that are associated with the formation, population, and extinction of habitable worlds.[10,11] The intellectual goals of this scientific discipline embrace three questions: How does life begin and develop? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond?

Astrobiology's multidisciplinary thrust provides an integrating theme, bringing together a substantial fraction of the issues in solar system exploration under the common thread of understanding planetary habitability. Rather than merely addressing the distribution of life in the universe, astrobiologists are concerned with clarifying the dynamical past of the solar system that led to terrestrial planets and their satellites, the interplanetary transport mechanisms responsible for cross-solar-system redistribution, the history of volatiles and organics, the processes (atmospheric and surficial) that affect the evolution of volatiles and the formation of habitable planets, prebiotic chemistry and the emergence of life, the influence of impactors on the survival of living systems, and all processes that lead to loss of the habitability of solar system objects. Astrobiology has both empirical and experimental dimensions. It seeks a historical accounting of the evolutionary processes that guided solar system formation and the emergence of life on Earth. At the same time, astrobiology aspires to understand, through multidisciplinary experimentation, the theoretical basis of how and why these processes occur.

Astrobiology as a theme provides a scientific organizational structure that integrates a wide subset of solar system issues and questions that span the origins, evolution, and extinction of life. This theme allows nonexperts to grasp the connections between different component disciplines within planetary science and to do so in a way that most people will appreciate as addressing core themes in human thought. Astrobiology and its connections to space science (and solar system exploration in particular) are the primary means by which NASA tries to implement one of its prime objectives—understanding life's origins and its distribution in the universe.

Astrobiology also has some priorities that are intimately connected to and rely on planetary exploration. Scientific objectives mentioned later in this survey of solar system exploration that directly address key questions in astrobiology include the following:

- Determination of the composition, abundance, and distribution of organic materials in the solar system;
- Exploration of both the potential oceans where life might emerge and the radiation environment at the surface and near-surface regions of Europa and the other Galilean satellites;
- Detailed determination of the elemental, chemical, isotopic, and mineralogical composition of the surfaces and upper crusts of planets and satellites (including Mars, outer solar system satellites, and icy objects);
- Investigation of the nature of atmospheric evolution and geochemistry on Venus and Mars relative to that on Earth in order to understand the potential for planetary evolution into habitable versus sterile worlds;
- Description of the detailed history of impactors and their potential influence on the evolution of terrestrial biospheres; and
- Further exploration of Mars, including a detailed search for subsurface liquid water and possible ground-ice inventories, full determination of surface mineralogy, and assessment of possible spatial and temporal juxtaposition of liquid water and sources of energy that could support life.

NASA's Astrobiology program has become a fundamental part of the solar system exploration strategy. **The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space-science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that will address key questions in astrobiology and planetary science.**

The goals for solar system exploration advocated in this report are sufficiently comprehensive to be resilient to the kind of minor readjustments in focus just described. In a real sense, today's objectives, as rephrased at the beginning of this section, define what the SSE Survey believes solar system exploration is and should be. However, as discoveries are made, changes in emphasis among these thrusts are inevitable. Today, solar system exploration focuses predominantly on questions of habitability and the possible existence of extraterrestrial life. The President's 2003 budget, for example, proposes the New Frontiers program with precisely this overarching goal.[12] The SSE Survey interprets this objective broadly, since any plan to address the possible existence of extraterrestrial life presupposes an extensive investigation of planetary evolution and of the planetary conditions that are conducive to the development of living organisms. In this regard, it should be noted that some of the primary goals of astrobiology can be met most efficiently through understanding particular planetary bodies and the way that they fit into the broad context of the solar system as a whole.

It is difficult to judge with confidence the degree to which the goals of the international community have altered to parallel those of the United States. Certainly the Soviet program shared the same early emphasis on lunar exploration and sample return, but it was originally more clearly focused on robotic investigations and techniques. Soviet reconnaissance missions to Venus and Mars quickly followed, with significant successes in robotic landings on the hellish surface of Venus.

Reconnaissance of the solar system by other nations experienced great success in the 1980s, with the first explorations of Comet Halley's nucleus by the Vega, Giotto, Suisei, and Sakigake spacecraft. Together, these missions filled in an almost-empty paradigm with unexpected details concerning the nature of cometary activity and the composition of cometary solids. Today the international community is mounting major geophysical and geochemical explorations of the Moon, Mars, comets, and asteroids with the Selene, Nozomi, Mars Express, Beagle 2, Smart 1, Rosetta, and MUSES-C missions.

RECENT ACHIEVEMENTS IN SOLAR SYSTEM EXPLORATION AND RELATED FIELDS

Our perceptions of our planetary neighborhood have been overturned since the space age dawned. Dots of light in the night sky have been transformed into exquisite worlds displaying bizarre phenomena—softly hued vortices swirling past Jupiter's Red Spot, enormous canyons and outflow washes crisscrossing Mars, or austerely beautiful rings encircling each of the giant planets.

The remarkable diversity and activity of the solar system were totally unexpected by planetary scientists and were forecast by just a few others, but mostly as science fiction. To illustrate the vitality of the discipline, it may be instructive to mention just a few of the findings since the publication of the last solar system survey less than a decade ago.[13] Most of these new understandings lead to additional questions.

To identify the most important discoveries of the past decade, the SSE Survey's Steering Group relied upon community input to its panels (see Part One), along with independent surveys of the scientific community and the public (see Appendixes C and D). Box 6.1 lists the most significant additions to our understanding of the solar system, while Box 6.2 outlines a half dozen of the most vexing and mysterious issues facing planetary scientists today.

A plethora of extrasolar giant planets, whose orbital characteristics have startled theoreticians, have been discovered elsewhere in our galaxy. Indeed, perhaps 5 percent of main sequence stars have massive companions, but the ubiquity of terrestrial-like planets remains unknown. Simultaneously, dust disks have been found to commonly enshroud most young stars, and even some aged ones. These observations suggest that the formation of planets is not unusual.

Researchers now wish to use ground-based telescopes and future spacecraft, such as Kepler and the Space Interferometry Mission (SIM), to observe a statistical sample of extrasolar planets in order to better understand the origin and evolution of planetary systems. Such studies will eventually be extended to the search for Earth-like planets and, ultimately, will characterize their atmospheres and their habitability with advanced orbital observatories such as the proposed Terrestrial Planet Finder (TPF) mission. Our understanding will be improved if we use the properties of our own gas giants to calibrate the processes exhibited in other planetary systems and to obtain clues to the primordial composition of the solar system.

Since the first Kuiper Belt object was detected in 1992, hundreds more have been sighted, disclosing a large extension to the solar system beyond Neptune. Similar structures are inferred to explain the oldest of the extrasolar disks. We are in the midst of compiling the first catalog of this territory that circumscribes the outer solar system so as to unravel its morphology and makeup and to allow an understanding of its relationship to the formation of the solar system.

BOX 6.1
Recent Significant Discoveries in Solar System Exploration

- Giant extrasolar planets and dust disks around many stars
- The Kuiper Belt, a large extension of the solar system beyond Neptune
- Possible subsurface oceans within the icy Galilean satellites
- Evidence that Mars might have been hospitable to life in its past
- Disputed evidence for life on ancient Mars in the meteorite ALH84001[1]
- Identification of the Chixulub crater on Earth and observations of the impacts of giant fragments of Comet Shoemaker-Levy 9 on Jupiter

[1]Included for its very positive, long-term policy implications rather than for the validity of the original claims.

BOX 6.2
Six Continuing Mysteries About the Solar System

- *The diversity of bodies in the solar system.* There are several distinct classes of objects now recognized in the solar system, including the terrestrial planets, the gas giants (Jupiter and Saturn), the ice giants (Uranus and Neptune), and the Kuiper Belt objects (including Pluto). Is this a common feature of other planetary systems, and, if so, what is its cause?
- *The sharp contrast between Earth and Venus.* Although similar in size, mass, composition, and solar distance, Venus is hellish while Earth has life. Did Venus once have an ocean's worth of water? Is the uniqueness of Earth's Moon a factor? What basic factors control climate?
- *The potential habitability of Mars.* Mars, the most Earth-like planet, is on the threshold of habitability. It has undergone significant changes over time, including massive climatic shifts, enormous magmatic events, the escape of volatiles, and the development and subsequent loss of a strong magnetic field. When and how did these changes occur? How did the complex interactions between various environmental factors affect prebiotic conditions and the possible origin, evolution, and survival of life?
- *The effect that the asteroids and comets have on Earth.* The small, wandering bodies of the solar system may determine the fate of Earth. What role have asteroids and comets played in delivering volatiles to Earth or in punctuating evolution through globally devastating impacts? Do these objects determine our ultimate fate?
- *Distant worlds of fire and ice, and possible life.* Activity abounds on the satellites of the outer solar system, from Io's fiery volcanoes to Triton's frigid geysers. What is the role of tidal heating? How many of the large icy moons hide subsurface oceans? Are these oceans habitable?
- *Nature of the Kuiper Belt and its myriad objects.* What is the diversity of compositions among Kuiper Belt objects? How many Pluto-sized or larger Kuiper Belt objects exist? What is the relationship of Kuiper Belt objects to comets, Trojans, and Centaurs? And, where does the Kuiper Belt end?

The discovery of possible subsurface oceans on several Galilean satellites has led to the recognition of a possible but unexpected abode for life beyond Earth. The current goals are to identify and determine the extent of any such subsurface ocean. Simultaneously we must rethink our ideas of habitable zones.

Evidence continues to accumulate indicating that water flowed on or near the martian surface in geologically recent times. This, together with indications of subsurface reservoirs of ice and geological activity, suggests that the Red Planet might have been hospitable to life in its past. We now should continue to document the nature of any past habitable climate and to characterize the extent of subsurface water and ice to see how closely they approach the surface. In situ investigations for water and evidence of past or present life should also be conducted.

Acceptance of the possibility of extraterrestrial life has progressed markedly during the past decade. Illustrating this are claims made for extinct life forms in the ancient martian meteorite ALH84001. While these claims have been sharply disputed, the debate has been on scientific terms and has concerned the validity of the evidence. This new perception in part also results from the concurrent discovery of terrestrial extremophiles. This discovery encourages a continuing search for and examination of other martian meteorites for biological evidence. Also, samples of known provenance should be returned to Earth for their mineralogical and isotopic characterization and ultimately to verify any in situ biological evidence.

As a final example of the advances made in the last decade, scientists in the 1990s realized the crucial role of impacts in altering life's path once they identified the Chixulub crater in the Yucatan as responsible for the Cretaceous-Tertiary (K-T) extinctions on Earth. In the same period, the pummeling of Jupiter with the remnants of Comet Shoemaker-Levy 9 reminded us all of the ubiquitous and continuing role of collisions in shaping planetary bodies. As a result of these findings, we now recognize that we must survey the skies for threatening

NEOs and maintain a watch for potential impactors. To make these identifications useful, we also need to determine relevant physical and compositional properties of potential impactors, including comets.

THE RELATIONSHIP OF SOLAR SYSTEM EXPLORATION TO SCIENCE AND ENGINEERING DISCIPLINES

The success of a solar system exploration mission relies crucially on the well-being of a wide range of scientific investigations and effective engineering. To be of value, missions not only must reach their targets quickly and with adequate power and stability, but also must produce significant scientific data that address the scientific goals noted previously. Scientific investigations are usually drawn from various established disciplines, including planetary science, geophysics, geology, atmospheric physics, cosmochemistry, fluid mechanics, meteoritics, space plasma physics, astrobiology, and aeronomy—to name but a few.

This point is made to emphasize the wide array of scientific disciplines that are informed by solar system exploration. The interaction between the disciplines and missions flows both ways—solar system exploration missions rely on a healthy scientific community for support and direction, and the value of the missions is dramatically enhanced by research that capitalizes on returned data. The nation's solar system exploration enterprise is driven by the high-level public goals outlined above, but it is not possible without strong support for the scientific and engineering backbone of the program. This support is currently lacking in several areas, which are detailed later in this report.

THE SOLAR SYSTEM EXPLORATION PROGRAM AT NASA: INTERRELATIONSHIPS

Relationship with Other Science Programs

Solar system exploration is currently overseen by two components of NASA's Office of Space Science (OSS): the Mars Exploration Program (MEP) office and the Solar System Exploration Division. This dual responsibility is recent and was apparently imposed to ensure that the exploration of Mars could progress at as rapid a pace as possible without being fettered by any problems that might arise in the more general program. The Solar System Exploration program is strongly coupled scientifically to other separately managed programs in NASA. Within the OSS, the strongest scientific and programmatic bonds are to the Sun-Earth Connections Division and the Astronomy and Physics Division.

The Sun-Earth Connections (SEC) Division sponsors research in solar and space physics with particular emphasis, as its name implies, on the Sun's effects on the terrestrial space environment. However, space physics research is not only concerned with solar-terrestrial relations but also encompasses study of the space environments of other solar system bodies. SEC strategic planning documents thus typically include missions to investigate planetary magnetospheres, ionospheres, and upper atmospheres.[14] A major thrust in the Sun-Earth Connections Division is the Living With a Star program—its purpose is to understand these Sun-Earth connections for very practical applications. This program overlaps with planetary science by aiming to help unravel how planets interact with solar insolation and the heliosphere, in order to understand the past and future climate and the gaseous and plasma environments of one very well studied planet.

The astronomy and astrophysics flight program conducted by the Astronomy and Physics Division is managed as two separate thematic groups, Structure and Evolution of the Universe and Astronomical Search for Origins. Roughly speaking, the former's activities are mostly devoted to high-energy astrophysics, whereas the latter's activities are devoted to less-energetic phenomena that are more relevant to the interests of solar system exploration, but not exclusively so. Planetary science has benefited enormously from Astronomical Search for Origins missions such as the Hubble Space Telescope (HST), and it expects more discoveries from the Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and other future space observatories (see below). Future Origins missions such as SIM and TPF are essential to extending planetary exploration beyond our own solar system, searching for other planetary systems, and then mounting spectroscopic investigations of extrasolar planets for evidence of biospheres. We see here examples of the strong interrelationship between studies relating to solar system exploration and astronomical origins. One provides a very detailed look at one example of planetary formation and evolution, while the other provides many examples of a wide variety of systems with different structures and at different stages of evolution.

Planetary science also has strong scientific links to NASA's Office of Earth Science (OES). Earth is the most intensely studied planet from space. Hence the science and observational techniques developed in OES are vital for the continuing development of planetary science and observations. The major thrust in OES is the Global Change program, from which planetary science will gain an understanding of Earth as a terrestrial planet among the four inner planets and will obtain data essential to understanding the origin and evolution of a terrestrial planetary biosphere.

Studies of the atmosphere and plasma environment of solar system bodies have been an integral part of the general solar system exploration effort since the launch of Mariner 2 in 1962 and are traditionally supported by NASA's Solar System Exploration program. Historically, some small but very important funding has also come from NASA's space physics activities and the National Science Foundation's astronomy and atmospheric science programs. This organizational arrangement made sense in the past and will continue to do so in the future, especially for in situ studies, because spacecraft traveling to various solar system bodies can and should carry a wide range of instrumentation. Examples of such successful undertakings are the Voyagers and the Galileo and Cassini orbital missions, as well as smaller ones such as Pioneer Venus. Comparative aeronomy and magnetosphere studies allow the knowledge of basic physical processes acquired through the study of the geospace environment to be applied to other solar system objects and afford a critically important opportunity to test our understanding of these processes by observing how they operate in other settings. Moreover, not only are there important connections between space physics and planetary science with regard to scientific themes relevant to both disciplines, but the instrumentation used in terrestrial space physics research and that used in solar system exploration also frequently have a common heritage.

Given the crosscutting interests among solar system exploration and terrestrial aeronomy and space physics studies, it is not surprising that the Space Studies Board's concurrent Solar and Space Physics Survey Committee also addresses some aspects of solar system exploration.[c] However, the nature and relative timing of these two somewhat parallel NRC studies did not permit as much direct coordination as would have been wished. Therefore, the recommendations associated with solar system exploration from these studies may advocate some different exploration strategies and priorities. These differences can and should be easy to resolve within the OSS. The excellent past cooperation between the different components of the OSS and among the scientific communities has encouraged and led to major advances in the field (e.g., the putative discovery of an ocean at Europa by magnetic-field observations) as well as exploration efficiencies. The SSE Survey strongly encourages the continuation of this cooperative exploration strategy.

Relationship with the Human Exploration Program

The Solar System Exploration program currently has no strong scientific or programmatic ties to the human spaceflight activities conducted by NASA's Office of Space Flight (OSF), although strong interactions occurred during the Apollo program.[15] The planetary program does, however, rely on the OSF for the procurement of launch services. The major thrust in the OSF is the construction of the International Space Station (ISS), with which no obvious connection with planetary exploration exists other than the potential of the ISS to serve as a future transportation node to the planets for both humans and robots.

Eventually there must be a strong coupling between robotic and human space exploration. Scientific exploration of the solar system and the scientific utilization of the space environment provide the impetus for human

[c]In its moderate program category, for example, the Solar and Space Physics Survey Committee assigned high priority to a Jupiter Polar Mission, a dedicated space physics mission to study high-latitude electrodynamic coupling between Jupiter's ionosphere and magnetosphere.

exploration beyond Earth orbit, and they are a prerequisite for sending humans to other worlds.[16] Robotic missions, for example, will collect the data necessary for sending astronauts to Mars and back safely.[17] These precursor experiments and measurements would provide information on target selection, surface physics and chemistry, the threat that high-energy particles pose during travel, and so on.[18] In the long run, human exploration of our celestial neighborhood is a driving force in its own right, but it will also furnish opportunities for significant science accomplishments.

The SSE Survey is not convinced that human exploration beyond Earth orbit will raise major issues for the planetary science community during the coming decade. Nevertheless, it would be a mistake for scientists to dismiss out-of-hand those individuals aspiring to return to the Moon, to walk on Mars, or to exploit the resources of near-Earth objects. This is true if for no other reason than to avoid future conflicts over limited resources. A prime lesson from recent human exploration activities is that prior planning by scientists might preclude a "shotgun wedding" sometime in the future.

ISSUES REGARDING THE INFRASTRUCTURE OF THE SOLAR SYSTEM EXPLORATION PROGRAM

It is far beyond the scope of this survey to give an exhaustive analysis of the current performance of the entire scientific and programmatic infrastructure of U.S. solar system exploration activities. However, the SSE Survey became aware of several controversial issues concerning the way this infrastructure currently operates. It is hoped that raising these issues will help the audience for this report recognize the "big picture" of how solar system exploration is practiced today; this identification may also aid in rectifying some of its deficiencies.

Research and Analysis Programs

It is largely through the work supported by research and analysis (R&A) programs within the Office of Space Science that the data returned by flight missions are converted into new understanding, advancing the boundaries of what is known. The research supported by these programs also creates the knowledge necessary to plan the scientific scope of future missions. Covered under this line item are basic theory, modeling studies, laboratory experiments, ground-based observations, long-term data analysis, and comparative investigations. The funds distributed by these programs support investigators at academic institutions, federal laboratories, nonprofit organizations, and industrial corporations. R&A furnishes the context in which the results from missions can be correctly interpreted. Furthermore, active R&A programs are a prime breeding ground for principal investigators and team members of forthcoming flight missions.

Healthy R&A programs are of paramount importance and constitute a necessary precondition for effective missions. This conclusion has been stated repeatedly and forcefully before,[19] and it is shared by NASA's Office of Space Science. The three R&A clusters (i.e., Origin and Evolution of Solar System Bodies, Planetary Systems Science, and Astrobiology and Planetary Instrumentation) most closely associated with solar system exploration were supported at the level of $96 million in FY 1999. This level is now expected to rise at about 3 percent per year above the underlying inflation rate for several years. This proposed rise is included in the President's FY 2003 budget.[20] Nevertheless, serious problems remain with these programs. The ratio of submitted to funded proposals is typically 3 to 1, which—the SSE Survey believes—is too high, since at this rate new proposals can rarely be funded. Also, the availability of authorized funds is often subject to delays and, in recent times, the value of the median grant has fallen to below $50,000 per annum, a level generally too small to support a researcher or a tuition-paid graduate student.[21]

The SSE Survey agrees with the Space Studies Board recommendation that NASA should routinely examine the size and number of grants to ensure that the grant sizes are adequate to achieve the proposed research.[22] The Survey supports the budgetary proposals that would steadily expand solar system exploration R&A programs. **The SSE Survey recommends an increase over the decade 2003-2013 in the funding for fundamental research and analysis programs at a rate above inflation to a level that is consistent with the augmented number of missions, amount of data, and diversity of objects studied.**

R&A programs are not currently—and in the opinion of the SSE Survey should not be—tied to specific mission goals. Thus, individual research projects do not correspond to particular missions. Nevertheless, as the breadth and depth of the space exploration missions increase, the R&A programs should expand and be redirected correspondingly. Therefore, in the broadest sense, R&A programs must be responsive to the current mission opportunities even if they are not rigidly coupled to them.

Previous NRC studies have shown that, after a serious decline in the early to mid-1990s,[23] the overall funding for R&A programs in NASA's Office of Space Science has, in recent years, climbed to approximately 20 percent of the overall flight-mission budget.[24] Figures supplied by NASA's Solar System Exploration program show that the corresponding value for planetary activities is closer to 25 percent and is projected to stay at about this level for the next several years. The SSE Survey believes that this is an appropriate allocation of resources.

Creation of Intellectual Capital

Finally, to maintain and enhance the scientific productivity of the entire solar system exploration enterprise and to ensure the creation of new intellectual capital of the highest quality in the field, **the SSE Survey recommends the initiation of a program of Planetary Fellows, that is, a postdoctoral program analogous to the Hubble and Chandra fellowships, which have done so much to nurture the next generation of astronomers and astrophysicists.** The purpose of this program would be to allow the brightest young investigators the opportunity to develop independent research programs during their most creative years. These would be prestigious, multiyear fellowships, based solely on highly competitive research proposals and tenable at any U.S. institution.

TELESCOPE FACILITIES: AN ESSENTIAL ELEMENT OF AN INTEGRATED SOLAR SYSTEM STRATEGY

Ground-based Telescopes

Two major scientific findings of the past decade, according to a ranking by planetary scientists (see Box 6.1 and Appendix C), were made using ground-based telescopes. The discoveries of extrasolar planets and of the Kuiper Belt have had an undeniable impact on our perception of our surrounding solar system and thus on the optimal strategies for future spacecraft missions.

Except for the major planets out to and including Saturn, all of the bodies of the solar system, including all those visited by spacecraft, were discovered by ground-based telescopes. Spacecraft provide invaluable in situ data on objects that were first identified from the ground. Utilization of the enormous discovery potential of ground-based telescopes is an essential part of an integrated strategy for solar system exploration.

Telescopes are vital in several ways. First, they provide the targets to which flight missions can later be directed. A prime example is that of the Kuiper Belt, which emerged in the 1990s as a vast, unexplored (and previously only postulated) "third domain" of the solar system beyond the realms of the terrestrial and giant planets. Even our yet-preliminary understanding of the dynamics of the objects beyond Neptune has led to wide acceptance of the outward migration of proto-Neptune at the solar system's dawn.

Another example of a "found" population is that of the near-Earth objects, which are now understood to pose a potential impact threat to Earth, but also could be exploitable both for sample return and as springboards for future human exploration missions.[25] NEOs present such attractive targets for spacecraft missions because some of them require the expenditure of less energy for rendezvous than that needed for any other planetary bodies. For this reason, some have argued that, in the long term, NEOs may become economically attractive sources of minerals and metals that are comparatively inaccessible on Earth.

NEOs include both asteroids and dormant comets. While the existence of this population has been recognized for many decades, systematic surveys conducted over the past 5 years have managed to discover only about two-thirds of the NEOs with sizes greater than 1 km that are thought to exist. It is also just within the past decade that the terrestrial hazard from these bodies has been widely accepted.

A second way in which ground-based telescopes are important is that they provide ongoing support for spacecraft missions, both before and after the mission. As an example, NASA's Infrared Telescope Facility's (IRTF's) thermal imaging of the Galileo probe's entry site showed that the probe descended through an atypical "hot spot" in Jupiter's cloud tops. This knowledge has proven crucial to the scientific interpretation of the compositional data returned by the probe, and in particular in explaining why the measured water abundances were unexpectedly low. Similarly, the success of the Stardust and Deep Impact missions crucially depends upon ongoing ground-based characterization of their target comets. The mission-funded studies of the Deep Impact target, for example, have greatly reduced the volume of parameter space that must be considered by the mission designers. Moreover, events associated with the impact into the target will be observed by telescopes around the world, complementing observations made by the spacecraft's instruments. Another good example of mission support concerns ground-based studies of the physical characteristics of the asteroids Gaspra and Ida prior to the encounters of the Galileo spacecraft.

In a much broader sense, Earth-based observations provide the context for mission results. Earth-based studies alone have allowed us to develop taxonomic systems for asteroids and comets. It is through these classification schemes that it is possible, for example, to expand the interpretation of results from the Near-Earth Asteroid Rendezvous (NEAR) mission's studies of Eros to other similar asteroids.

Ground-based planetary radar facilities at Arecibo, Puerto Rico, and Goldstone, California, are used for detailed, physical characterization of many different bodies in the solar system. Much of the initial reconnaissance of Venus's surface was conducted with the Arecibo telescope, providing valuable input to and context for subsequent radar studies undertaken by the Magellan mission. The same facility has also identified highly reflective areas on Mercury thought to be due to ice located in permanently shadowed craters in the planet's polar regions. Similarly, the Goldstone facility has been used to study the bulk surface properties of the icy Galilean satellites. Both facilities have been employed to "Doppler-image" several near-Earth asteroids, providing information on their shape, surface roughness, composition, and spin state, in addition to dramatically improving measurements of their orbits.

Although important to solar system exploration, planetary radar studies at both Arecibo and Goldstone are highly leveraged activities. Roughly 90 percent of the Arecibo budget is provided by NSF to support general radio astronomy studies. Similarly, the bulk of the Goldstone funding arises from its role as a communications hub in NASA's Deep Space Network (DSN).

NASA continues to play a major role in supporting the use of Earth-based optical telescopes for planetary studies. It funds the complete operations of the IRTF, a 3-m-diameter telescope located on Hawaii's Mauna Kea. In return for access to 50 percent of the observing time for non-solar-system observations, the NSF supports the development of IRTF's instrumentation. This telescope has provided vital data in support of flight missions (as described above) and will continue to do so. NASA currently purchases one-sixth of the observing time on the privately operated Keck 10-m telescopes. This time was purchased to test interferometric techniques in support of future spaceflight missions such as SIM and TPF. However, the fraction of the NASA time available for general solar system observations is rapidly shrinking as the Keck interferometers come online.

The SSE Survey recommends that NASA continue to support ground-based observatories for planetary science, including the planetary radar capability at the Arecibo Observatory in Puerto Rico and at the Deep Space Network's Goldstone facility in California, the Infrared Telescope Facility on Mauna Kea in Hawaii, and shares of cutting-edge telescopes such as the Keck telescopes on Mauna Kea, as long as they continue to be critical to missions and/or scientifically productive.

Interestingly, NASA has no systematic survey capability to discover the population distribution of the solar system bodies. To do this, NASA relies on research grants to individual observers who must gain access to their own facilities. The large NEOs are being efficiently discovered using small telescopes for which NASA provides instrumentation funding, but all the other solar system populations—for example, comets, Centaurs, satellites of the outer planets, and Kuiper Belt objects—are being characterized almost entirely using non-NASA facilities. This is a major deficiency, since a large-aperture survey telescope will be essential to support the flight-mission strategy (for example, by selecting and characterizing key targets of the mission) developed in Chapter 8, where the SSE Survey makes a strong related recommendation.

Space-Based Telescopes

Many significant discoveries in planetary science have come from Earth-orbiting telescopes operating at a variety of different wavelengths. These discoveries include the following:

- The unexpected detection of strong x-ray emissions from comets;
- Studies of jovian atmospheric chemistry based on HST observations of the impacts of Shoemaker-Levy 9 into Jupiter; and
- The discovery of a star's strong water emission that is best interpreted as the evaporation of icy bodies in the outer planetary system of that star.

The anticipated launch of SIRTF and the flights of SOFIA will provide additional superb tools for planetary science, particularly in determining absolute sizes and the surface reflectivity of numerous objects in the Kuiper Belt. The Long Duration Exposure Facility (LDEF) made major contributions to our understanding about the nature and provenance of interplanetary dust.

With the exception of the recently selected Kepler mission in the Discovery program, these orbiting telescopes have been built and operated under the auspices of NASA's nonplanetary programs. Indeed, because of the commonality of the tools used by planetary astronomers and their colleagues interested in stellar, galactic, and extragalactic phenomena, virtually every major astronomical mission that has flown has made some significant contribution to solar system exploration. The close coincidence between the instrumentation used by planetary and other astronomers makes it unnecessary for the SSE Survey to recommend a major Earth-orbiting telescope devoted exclusively to solar system studies. The Survey prefers to rely on the Discovery and, where appropriate, the Explorer lines to generate appropriate candidates. **It is noted, however, that using Earth-orbiting facilities for planetary observations imposes special constraints—notably the need to track moving targets—and the SSE Survey endorses the incorporation of this technically difficult but essential capability on all relevant astronomical telescopes.**

DATA ARCHIVING

The Planetary Data System (PDS) was developed to provide the archiving function through working scientists; in astrophysics, data archiving is provided by the operating entities for the Hubble Space Telescope and the other Great Observatories. The budgets for early Discovery missions (e.g., Lunar Prospector) and technology-demonstration activities (e.g., the Department of Defense's Clementine and NASA's Deep Space 1) made no provision for archival products. As a result, data from these missions have been very little analyzed. The recent success of the NEAR mission and its return of a huge volume of data—an order of magnitude more than when the mission was planned—have highlighted the importance of archiving as a separate activity within solar system exploration. These events have also illustrated many of the pitfalls in establishing an archive from a highly productive mission that was budgeted in the Discovery range. The risk exists that the scientific return from solar system exploration missions will be smaller than ideal as small, principal-investigator-led missions proliferate. Although it is too early to judge, it appears that the Mars program has already begun to ensure that archiving will be well handled.

At present, the PDS appears to have insufficient resources for the job it has been given. Moreover, only rarely is the PDS involved as a scientific partner at a mission's outset. By contrast, a new instrument for HST is developed with consideration for the pipeline processing and archiving from the outset. The PDS faces two distinct challenges in the immediate future—the diversity and number of missions on the one hand and the volume of data on the other. The interaction with many different missions is currently severely stressing the capability of the PDS. On the technological front, the Mars Reconnaissance Orbiter alone is projected to return at least 300 terabytes of data, a volume exceeding that of all the Great Observatories combined and presenting a major challenge to the PDS.

The increasing attention paid to archiving plans in the recent rounds of Discovery selections has been a step forward, as has the recent support by the Mars program, although the overall situation remains unsatisfactory. The SSE Survey notes, for example, that all Discovery proposals are required to budget 1 to 2 percent of their total cost for education and public outreach (E/PO), a valuable activity that is also highly leveraged with external resources. The total amount of money spent on preparing archival products by any mission is small compared to this, with the only leveraging being in the PDS budget, except in the special case of non-NASA missions for which there is large leveraging through the outside agency. This is the funding that is intended to provide the complete archival product, ready for use by the research community. The PDS is funded, at present, just to maintain suitable standards, to advise the missions, and to distribute the archival products, not to prepare them. The SSE Survey notes that in many cases the experience resident in the PDS could lead to more efficient preparation of archives if the PDS scientists were involved at the earliest stages. Furthermore, substantial community demand exists for access to the large databases of Earth-based data produced through NASA's R&A programs—data that are in general not archived with the PDS for lack of resources. Enhancements to either the PDS or mission budgets would enable data archiving.

The SSE Survey strongly encourages exploration of ways to accomplish the following:

- **Improve the early involvement of the PDS with missions;**
- **Increase the PDS budget and streamline its procedures, while not lowering standards or eliminating peer reviews, in order to deal with the data, perhaps considering the function to be funded at a fixed fraction, such as 1 percent of the mission development and operations budget in addition to a small base budget, to ensure that the PDS can cope with varying amounts of archiving; and**
- **Ensure that missions as well as R&A projects producing large data sets have adequate funding for proper archiving.**

DATA-ANALYSIS PROGRAMS

A crucial task in getting scientific value from solar system exploration missions is to properly organize and adequately fund strong data-analysis programs (DAPs). In order to maintain momentum, DAPs for the community should be ready to support investigators immediately upon the delivery of ready-to-use data to the PDS. This would allow continuity for investigators on short-lifetime missions that have reached their end, and it would allow outsiders sufficient monies to promptly attack scientific questions based on the data. In addition to providing adequate funding, several other procedural steps must occur.

Preliminary versions of the ultimate archival materials must be delivered regularly throughout the mission to avoid delays in the availability of final products at the mission's end. This requires the involvement of the PDS as a scientific partner very early in the mission. It also requires describing, in some detail, the content of the archive sufficiently before the DAP proposals are due, so that proposers can make sensible proposals before the data themselves become public. It also mandates that investigators be able to propose across missions when scientific questions clearly transcend individual missions. NASA's stated intent to merge—albeit a number of years in the future—the DAPs for individual Discovery program missions into a single DAP for the Discovery program appears to be a step in the right direction. This could allow a researcher, for example, to coherently analyze data from the several missions to comets, and, similarly, a Mars-data analysis program could allow a researcher to comparatively interpret data from several missions of the Mars program. The SSE Survey urges that these data-analysis programs be kept sufficiently flexible so that it is structurally easy to add a component for analyzing data from other sources, such as from technology missions—Deep Space 1 data from comet 19P/Borrelly (Figure 6.1) represents a current example—or from foreign missions archiving with the PDS (Mars Express, for example).

NASA's Great Observatories, most notably through the Space Telescope Science Institute (STScI), but also other Great Observatories, have conclusively demonstrated the great value of a uniform, readily accessible archive coupled with support for the analysis of the data by the original investigators as well as by others who use the archived data for research. Each scientific user of a Great Observatory is funded to analyze the data obtained in his or her program, and the mission itself maintains a long-term archive. Because the Great Observatories are

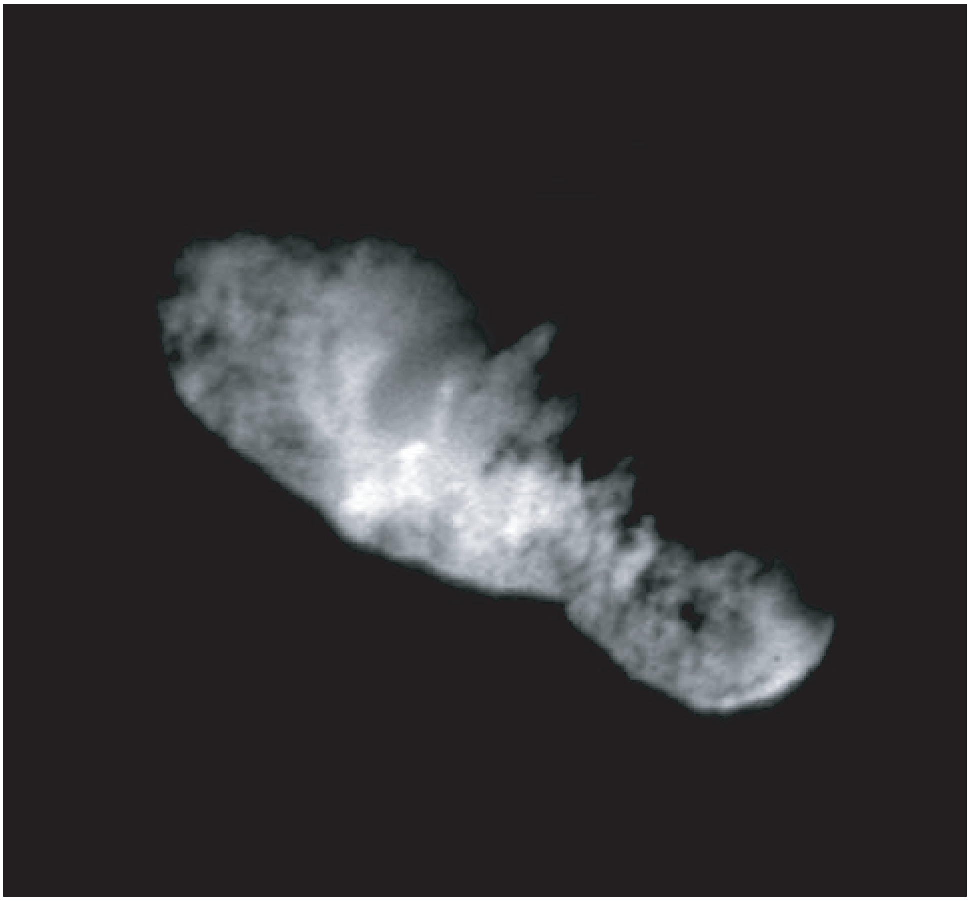

FIGURE 6.1 A close-up image of the nucleus of Comet 19P/Borrelly obtained by the Deep Space 1 spacecraft. Courtesy of NASA/JPL.

archiving large volumes of data from only a few instruments operated over a very long time, the archiving process becomes highly automated, and data appear in the archive typically within days of being obtained and long before they become publicly available. The data in the archive become public after a short period, varying from one observatory to another, but usually in no more than a year and sometimes immediately. Once data are in the public domain, other investigators can obtain funding to analyze them. Because the observing programs are publicly known even before the observations are carried out, investigators can plan ahead to apply for support to begin analysis immediately after the proprietary validation period has ended. STScI finds that the typical datum (one image or spectrum) is used in at least several separate investigations beyond that of the original observer. The accumulated download of data is many times larger than the total amount of data in the archive. This archival research has led to major discoveries and also has dramatically improved the planning for future missions.

The success of astrophysical archives has given birth to the National Virtual Observatory (NVO) initiative that should make the archives even more productive in the future.[26]

In solar system exploration, examples of the value of archives are diverse. The Geosciences Node of the Planetary Data System, for example, digitized the microfilm data from the Viking Labeled-release Experiment, thus enabling a new type of investigation searching for evidence of circadian rhythms in the data. The Small Bodies Node (SBN) provided archival interpretation of the Giotto trajectory for an investigator seeking to discover if the nucleus of Comet Grigg-Skjellerup is binary. The archives are also used extensively for planning future missions, all the way from the proposal stage through details of spacecraft and mission design. Investigators have written letters to the SBN highlighting how they have used the online database, particularly the database on Earth-based comparative data on comets and asteroids, to plan Discovery program proposals.

Solar system exploration missions operate entirely differently from the Great Observatories in many ways. The missions tend to be of fixed duration, and all but the Flagship missions usually have short lifetimes that make it impractical for the mission teams to either develop or maintain a long-term archive. The mission teams rarely have any expertise in archiving, and the data products from the teams often have grossly different formats with widely varying degrees of documentation. Furthermore, solar system exploration missions do not themselves include extensive, funded programs for guest observers, who effectively serve as user-reviewers of the archival pipeline. Data-analysis programs, established to allow research on the information returned from solar system exploration missions, have been hit-or-miss, often underfunded, of too short duration (e.g., the Venus Data-Analysis and Jupiter Data-Analysis programs), or nonexistent (e.g., the Galileo Europa and Millennium Mission extensions). On other occasions, funding is delayed to such an extent that research programs risk losing momentum (e.g., for the NEAR mission).

To obtain the maximum value from the scientific data returned from solar system exploration missions, it is essential to properly execute two intimately related activities. The first of these is to ensure that the archiving entity, the Planetary Data System, has the necessary resources for the job and is treated as an important scientific component of each mission from the outset. The second is to dramatically improve the data-analysis programs.

SAMPLE-RETURN FACILITIES

As part of NASA's Solar System Exploration program, samples will be returned from extraterrestrial bodies. Sample-return missions already under way include the Stardust and Genesis missions of NASA and the MUSES-C mission of Japan's Institute of Space and Astronautical Sciences (ISAS). Samples from these missions carry a planetary protection designation of "Unrestricted Earth Return."[27] They will be curated in dedicated facilities at the Johnson Space Center and distributed to qualified scientists for investigation. Samples returned from objects of biological interest (e.g., Mars and Europa) are subject to quarantine restrictions in a sample quarantine facility that can preserve the pristine nature of the samples and prevent back-contamination of Earth.[28]

Mars Quarantine Facility

Several NRC studies outline the containment requirements for samples returned from Mars.[29] With the exception of samples returned from Europa, there are few constraints on samples returned from small solar system objects.[30] The recent NRC report on the Mars Quarantine Facility (MQF) stresses that a minimum of 7 years will be required for the design, construction, and commissioning of the MQF, and that it must be operating up to 2 years prior to the arrival of martian samples. The purpose of the MQF is threefold: to sequester unaltered samples until biohazard testing is complete, to preserve the pristine nature of the samples, and to release samples deemed to be nonhazardous to a sample curation facility for allocation for further scientific study.

The technology required for containment and testing for pathogens is well developed. Biohazard assessment must also consider the potential ecological threats posed by returned samples. Sample containment must preserve the samples in a pristine condition, without inorganic and organic contamination. Technology for the preservation of samples similar to that used for lunar samples in the Lunar Curatorial Facility at the Johnson Space Center is well developed. However, the combination of biocontainment and preservation of samples in their pristine condition requires a unique design for the MQF that no currently existing facility provides. Another important design feature should be the potential for expansion, if early findings of definite evidence of extraterrestrial life warrant the need for all studies to be performed under containment.[31] The cost of building such a specialized quarantine facility needs to be investigated.

In addition to developing the technology to satisfy the design constraints for the MQF, it is also important to initiate a program to develop key research and analytical tools. These include, for example, the development of criteria for the following:

- Biohazard assessment,
- Definition of life and of standards for life detection that minimize sample size requirements,
- Sterilization of samples for potential early release, and
- Release from containment of samples deemed to be safe.

A vigorous research and analysis program must address these issues:

- Enhanced sterilization techniques that will minimally compromise the integrity of returned samples, and
- Highly sensitive techniques for life detection.

The sample-handling requirements for geochemical and biological investigations and for specific biohazard testing are not necessarily compatible. The NRC has recommended that an advisory committee oversee the design and construction of the MQF and that this group "will be ultimately responsible for the disposition and handling of samples in the MQF until they are judged to be safe for release."[32] This committee should also be cognizant of the processes for collecting the samples on Mars and for allocating the samples for scientific study once they are released to the Mars Curatorial Facility. **The SSE Survey endorses the concept that a single advisory structure supervise all aspects of returned Mars sample collection, containment, characterization and hazard assessment, and allocation. This advisory structure might be international in composition.**

Sample Curatorial Facilities

To prevent cross-contamination between samples from different planetary bodies, the samples must be handled in separate facilities. The Mars Curatorial Facility, for example, will be required once the martian samples are shown to be environmentally safe. Construction of such a facility is considered to be consistent with current practice and experience, for example, for lunar samples and Antarctic meteorites. Sample allocations from the Lunar Curatorial Facility and from the Antarctic Meteorite Laboratory are under the guidance of advisory committees (the Curation and Analysis Planning Team for Extraterrestrial Materials and the Meteorite Working Group). These advisory committees are the successors of the Lunar Sample Analysis Planning Team, which oversaw the preliminary examination of the returned lunar samples and lunar sample allocations. These committees best exemplify the advisory committee proposed above for the oversight and analysis planning for Mars samples.

The Need for an Early Sample-Return Program

When addressing the future of solar system exploration, it is clear that a natural process of maturation has occurred. Missions have progressed from reconnaissance flyby and orbiter missions, to detailed characterization from more sophisticated, long-lived orbiters and from landed missions with in situ investigations, to sample return from small bodies, and finally to future sample-return missions from planets, comet surfaces, and asteroids. Science questions tied to samples returned from diverse planetary environments form a prominent theme in the individual panel reports of Part One that lead to many of the specific mission recommendations for the next decade (see Chapter 8). This recurring emphasis on sample return is a direct result of the sophisticated level of scientific questions that can now be posed and answered. There is nevertheless a host of interwoven issues and requirements for each of the sample-return missions, many of which would benefit from a thorough and integrated approach.

These issues were addressed by some of the panel reports (see, for example, Chapter 2). The broad common categories that must be addressed by each mission include the following:

• Consideration of the means by which a sample is acquired and returned to Earth. Although each planetary environment is different, the technology required for implementation often applies to more than one situation. Experience gained in one environment may provide valuable benchmarks for another. Examples include these:

—Experience with end-to-end sequencing for lunar sample acquisition would provide confidence in undertaking the more complex Mars sample return;

—The architecture for returning samples from the Mars gravity-well could be comparable to that needed for a similar Venus activity; and

—Anchoring a spacecraft on and acquiring samples from a low-density, near-Earth object would provide experience needed for similar activities on a complex, multiphase comet nucleus (or vice versa).

• Requirements for the development and maintenance of Earth-based, state-of-the-art analytical capabilities to study the returned samples. Instead of developing instruments for launch into space, extremely capable and sophisticated instruments must be developed for use in Earth-based laboratories for data acquisition and the extraction of science information from the returned samples. A review of the analytical capabilities in U.S. laboratories for sample analysis has identified the need for the development of new instrumentation and for upgrading U.S. laboratories. In response, a start in this direction has been made by the new and fully competitive Sample-Return Laboratory Instrumentation and Data Analysis Program. There is a need to improve and to develop, on a continuing basis, novel, sensitive instrumentation and to develop the analytical techniques applicable to specific samples and new science questions. The development of a specific instrument normally takes 5 to 7 years. Gaining experience and developing techniques for such an instrument require an additional 2 years. While some instruments may become commercially available, it is more likely that, with adequate support, key novel instruments will be developed through the close interaction between industry and researchers.

• Need for appropriate analytical facilities along with personnel who have the expertise to use them. Diverse instrumentation is necessary for sample analyses. For major instruments, it is likely that the use will be shared by many investigators and that such instruments may reside in regional Centers of Excellence and require a facility-type operation. It is anticipated that most of these regional facilities will be associated with educational institutions and will help train multidisciplinary researchers. It is recommended that these analytical capabilities and experience working with very small samples be developed well in advance of sample return.

• Need for planetary protection and curatorial facilities to contain samples and for procedures to handle diverse samples. Such facilities for lunar samples are already in place and in use. Facilities for the Discovery missions Stardust and Genesis are under design. Appropriate facilities for diverse samples from environments with biological potential as well as from environments whose integrity must be maintained (e.g., temperature, pressure, composition) need to be implemented and sample-handling experience gained well in advance of sample return.

As we enter the detailed exploration phase of planetary exploration, sample return of the basic "ingredients" that compose the solar system will become an integral element of fundamental science return, and with it a host of new challenges need to be addressed. This will require support on a continuing basis for the preparation of and in conjunction with an exciting suite of sample-return missions. Such support can be provided through the identification of a new sample-return program comparable to Missions Operations and Data Analysis. Samples from Stardust, Genesis, and the ISAS mission MUSES-C will become available during the next 4 to 6 years. For the next decade and beyond, with the expectation of additional samples returned from the Moon, the surface of a comet, Mars, and possibly NEOs, a stable program will be required to ensure that the Earth-based component is sufficiently strong to fulfill the science objectives. **The SSE Survey recommends that NASA establish, well before samples are returned from planetary missions, a sample-return program to address analytical and facility issues and the training of researchers in an integrated manner. Such a program will allow focus on the optimization of science and technology resources.**

PUBLIC RELATIONSHIPS: OUTREACH AND EDUCATION

NASA has been engaged in education and public outreach activities since its inception in 1958. During the mid-1990s, the NASA Office of Space Science formalized an E/PO strategy that includes education communities, space scientists, and related NASA organizations.[33] The implementation of this strategy was formulated by an E/PO Task Group appointed by the Space Science Advisory Committee. A key element of the implementation is to "leverage" activities through collaborations with other organizations and institutions, such as planetaria. An integral part of OSS's E/PO goal includes training activities to help create a scientific workforce for the future. The program is well conceived to achieve these goals and on its way to becoming a hallmark for other governmental agencies.

The OSS E/PO is organized into four forums, each of which corresponds to OSS themes, including Solar System Exploration (SSE). The SSE E/PO forum, directed through the Jet Propulsion Laboratory, provides sustained efforts and continuity of educational activities beyond those of short-term missions or activities undertaken by individual researchers. Part of the OSS E/PO program is the concept of "brokers," which are regional centers with the goal of interfacing between the needs of various E/PO ventures and planetary scientists.

The OSS E/PO sponsors a wide variety of activities and collaborations, implemented through missions, research activities, formal education projects, and informal projects. For example, in the year 2000, some 614 events for educators were held across solar system exploration activities and involved more than 42,000 attendees; in addition, more than 600 public events were held, reaching more than 662,000 participants. Concurrently, 85 permanent museum exhibits were supported, and 11 traveling exhibits involving solar system exploration were developed.

Planetary missions provide an unparalleled opportunity to capture student and public attention in science, engineering, and exploration. Recognizing this high potential, all NASA flight programs are required to devote 1 to 2 percent of their total budget to E/PO. Typically, each flight project develops its own set of activities. The E/PO components developed through principal-investigator-led flight projects, such as Discovery missions, have been particularly effective. In these projects, E/PO is typically "leveraged" through other organizations (including non-NASA groups), identified and cultivated by the principal-investigator team. All recent planetary missions, including Galileo, Cassini, Deep Impact, Messenger, Contour, Stardust, and various Mars missions, have extensive E/PO activities.

Current NASA Research Announcements for OSS programs provide the opportunity for planetary scientists accepted for funding to submit proposals for E/PO activities as supplements to their research projects. The selection of these supplemental awards is based on the recommendations from reviews established separate from the science research review panels, but which include educators and scientists.

The formal education aspect of the SSE E/PO includes teacher preparation, student support, and funding of the National Education Standards. For teacher preparation, the SSE goal is to train 7,500 teachers annually, with the potential to reach 225,000 students. Student support is provided through programs such as Radio JOVE, which teaches the scientific method to students in grades 6 through 14 using radio astronomy to observe the Sun or Jupiter. National Education Standards have been derived for the United States.[34] To support the implementation of the standards, the SSE E/PO has developed a pilot program that demonstrates how results from solar system exploration can be used to meet specific curriculum requirements.

There is widespread agreement that a significant strength of the SSE E/PO program is the direct involvement of principal investigators with students, teachers, and the public. Particularly valuable are partnerships with organizations (e.g., the Planetary Society) and industry during missions. The opportunity to interact with active scientists and to ask questions is greatly appreciated by these audiences. Participation by students and teachers in projects, active missions, and scientific meetings is considered excellent first-hand learning experience. Similarly, secondary-school class participation in active research through the collection of data and interaction with scientists has been highly successful. However, these activities typically involve small numbers of people and substantial commitment by planetary scientists. Consequently, activities with a multiplier effect are considered to be more cost-effective. For example, activities such as NASA's Solar System Ambassadors program, in which individuals are identified within regions to serve as local contacts, have worked well. In addition, more of the results of solar system exploration should be incorporated into undergraduate and graduate curricula. This could be achieved by working closely with authors and publishers of textbooks, including offering help at the review stages of publication.

One significant issue associated with the various science principal investigator (PI)-led E/PO efforts is the general lack of recognition by institutions and peers for E/PO activities. Considerations of promotion and tenure place little weight on such activities, and E/PO publications are seldom considered to be significant in the PI's publication record. Consequently, most PIs conduct E/PO on the side, because they feel it is important, but understand that their efforts are unlikely to be recognized or rewarded.

Most of the current SSE E/PO principal-investigator-led activities appear to be focused on teachers and students, with relatively little attention given to the general public. Some planetary scientists noted that research-linked E/PO proposals for activities focusing on the adult population tend to be rejected within the current SSE E/PO framework. Although it is recognized that the OSS E/PO sets a priority on educating teachers and students, it is also important to educate the general population about broad science topics and more specifically, solar system exploration goals and results. Enabling interactions with active planetary scientists could be very effective for this purpose.

Nearly everyone agrees that having an E/PO program within SSE, and particularly the involvement of PIs is good. However, many planetary scientists view the SSE E/PO program as being excessively bureaucratic, especially when the broker-facilitator system is taken into account. Although many PIs consider this system to have merit in principle, they see it as ineffective in practice. Moreover, it is not clear how the lines of responsibility are drawn between NASA's Public Information and Education and Public Outreach offices or how the various activities are coordinated.

The requirement of incorporating E/PO for specific projects, such as Discovery missions, is considered meritorious, and most planetary scientists agree that the current funding levels of 1 to 2 percent are about right within the SSE program. In most implementations, planetary scientists and education specialists work hand-in-hand to derive innovative and effective activities for communicating solar system exploration to students, teachers, and the public. In many respects, these programs serve as models for SSE E/PO in general. E/PO activities proposed as part of the overall research program, however, have not worked very well, primarily because of the review process and the lack of sufficient funds. For example, many PIs put substantial effort into preparing "add-on" E/PO activities as part of their research grants only to learn later that very few of the E/PO activities were funded. Moreover, in many cases they received little or no feedback on their E/PO proposals.

In summary, the SSE E/PO program is considered to have a solid foundation and to be well organized and managed. An appreciable strength is the close linkage to active planetary scientists and flight projects, and the partnering with other programs, both within NASA and outside the space science program. Areas for improvement include better communication with the planetary science community, strengthening the review process for various elements of the E/PO program, and improving the linkages to nonflight research projects.

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